# MODEL DEFORMATION MEASUREMENTS AT A CRYOGENIC WIND

TUNNEL USING PHOTOGRAMMETRY

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#### ABSTRACT

A photogrammetric closed circuit television system to measure model deformation at the National Transonic Facility (NTF) is described. The photogrammetric approach was chosen because of its inherent rapid data recording of the entire object field. Video cameras are used to acquire data instead of film cameras due to the inaccessibility of cameras which must be housed within the cryogenic, high pressure plenum of this facility. Data reduction procedures and the results of tunnel tests at the NTF are presented.

#### INTRUDUCTION

Experimental testing of the cryogenic wind tunnel concept using a pilot facility (1) led to the construction of the NTF at NASA Langley (2). combination of high pressure (9 atm) and low temperature (100 K) expands existing wind tunnel testing capabilities. With temperature and pressure as variables, two of the aerodynamic parameters can be held constant while one of the parameters is varied to separate Reynolds number, Mach number, and dynamic pressure effects. Due to the increased dynamic pressure capability of the NTF some of the higher aspect ratio models may experience wing tip deflections of several centimeters. A method is required to measure this model deformation (wing deflection). Optical instrumentation to measure model deformation must be located within the outer high-pressure shell (plenum) of the NTF (Figure 1) since the plenum has no windows. The test section has a limited number of 6-inch-diameter windows, but equipment placed inside the plenum must be protected from the high-pressure cryogenic environment and may be inaccessible for long periods of time.

A number of techniques have been considered for measuring model deformation including moire and holographic contouring and a stereo-electro-optical tracking system which uses image dissector cameras (3,4,5). This report describes a photogrammetric approach chosen because of its inherent rapid data recording of the entire object field (i.e., scanning is not required as for single point techniques) and is based on earlier wind tunnel work at NASA Langley with film cameras (6). The inaccessibility for long periods

of time of cameras which must be housed within the facility prompted the selection of video instead of film cameras to acquire data (7). The feasibility of using video cameras for photogrammetry and procedures for distortion correction were established by Wong (8-10). A review and comparison of these procedures as well as data verifying the long-term repeatibility of electronic distortions for the cameras used at the NTF are presented in reference 11.

### EQUIPMENT

The video cameras are instrumentation grade, high resolution cameras operated at 875 scan lines. Newvicon tubes are used at higher lens F-numbers than possible with Vidicons to increase the depth of field. Standard television lenses of 50 mm focal length provide an adequate field of view. Quartz halogen lamps are mounted in the test section sidewalls and ceiling to illuminate the model under test.

The video tubes each have reseau grids on their faceplate in order to correct for electronic distortion. The reseaus consist of 7 x 9 arrays of equally spaced crosses which also serve as fiducial marks to aline successive video images and to reference the location of the photogrammetric principal point.

The video cameras are mounted in protective housings in the test section sidewall at the NTF. The cameras look over the fuselage at one of the wings of the model (Figure 2). The housings (Figure 3) are equipped with insulation and sheath heaters to maintain the cameras at 280 K and are pressure rated to greater than 9 atm. Vibration is monitored during tunnel runs with an accelerometer which is perpendicular to the optical axis of each camera.

Two techniques are used to prevent frost formation on the inside surface of the protective housing windows—electroconductive (EC) coatings and heated—air purge rings. The EC coatings are rated at 10 watts per square inch with 60 volts applied and have a transmission which exceeds 80% in the visible spectrum. The dry air supplied to the purge rings is heated by passage through a vortex tube. Each ring has a number of holes to direct

the heated-air flow over the inside surface of the windows.

Recordings of the video images are made with a video hardcopy unit which records video images on dry silver paper in a 17 x 23 cm format. The hardcopy unit takes 4 seconds to record a video image which is available for viewing after 11 seconds. The hardcopy of the video image is read with a monocomparator which has a resolution of 1 micrometer. The x,y location of targets read with the monocomparator are stored as a data file for later processing by a desktop computer.

A high resolution (10 MHz) video disc records up to 125 video image pairs when tunnel vibrations or model dynamics prevent use of the video hard-copy unit during a tunnel run. Permanent hard-copies are made of selected video images after the tunnel run is complete. A sequential switcher routes one from each camera to the disc recorder when the record button in pressed to efficiently utilize the storage capability of a single disc and to allow rapid data acquisition.

A test pattern generator, a sync source generator, a pattern mixer, time-date-number markers, a patch panel, and display monitors complete the list of video equipment at the NTF. The sync source generator causes the two video cameras to frame together. The pattern mixer aids in distortion correction of video images recorded on disc. The recorded video signal is fed through the pattern mixer to superimpose vertical lines on the image before routing to the hardcopy unit. Measurements of the waviness in the vertical lines (caused by jitter in the start of the horizontal sweep) can be used to correct the video images for disc recorder distortion.

### PROCEDURE AND DATA REDUCTION

In order to make photogrammetric measurements of model deformation the model must have identifiable targets. Currently targets are placed on a model by first spray painting the wing and part of the fuselage with blue layout fluid. White paint is then applied at selected spots on the wing so that the model is relatively dark with a number of small bright targets. If dark targets on a bright background are used rather than the reverse the adjustment of the light level of the ceiling and sidewall lamps is more critical and the video images obtained are harder to read in the monocomparator. At the high Reynolds numbers encountered at the NTF this technique may not be suitable for some models since boundary layer thicknesses are reduced and the effects of roughness on skin friction, transition, boundary layer separation, etc., are enhanced.

The locations and pointing angles in the tunnel coordinate system of cameras at the NTF are determined by space resection on the wing target points with no flow. Video images are recorded on the model set at roll angles that bracket the region of interest. The three video images are merged and treated as one image file for the space resection. Accurate values for model roll

and elevation from onboard sensors are required to determine the locations of the wing target points in the tunnel coordinate system necessary for space resection. This process of resecting on the wing jointly at several known roll angles can be repeated if it is suspected that the cameras have moved since the last resection.

After correcting for comparator error, the distortion correction is begun by transforming, using linear least squares, the video image data to the actual dimensions on the video tube face-plate, making use of the known locations of the reseau crosses. A transformation which allows for scale changes and quadratic terms in x and y is

$$x' = a_1 + a_2x + a_3y + a_4x^2$$
 (1)

$$y' = b_1 + b_2 x + b_3 y + b_4 y^2$$
 (2)

where x and y are the comparator coordinates and x' and y' are the coordinates after transforming to the tube faceplate. The scale change and quadratic dependence compensate for small variations in the electronic distortion as a function of time.

The distortion residuals for each reseau cross as well as the transformation coefficients necessary to transform the video image to the video tube faceplate are saved as a distortion correction data file for the particular video image. The distortion vectors are plotted (Figure 4) and compared to previous distortion plots to check for possible reading errors. If all of the reseau crosses are visible on the video image then distortion correction is begun for a given image point by first determining which four reseau crosses are its nearest neighbors. Once this procedure is completed bilinear interpolation is used to determine the corrections to be applied. Another method of distortion correction using high-order polynomials is described in references 8-10 and compared to bilinear interpolation in reference 11.

The bilinear equations may be expressed as

$$\Delta x = a_1' + a_2'x' + a_3'y' + a_4'x'y'$$
 (3)

$$\Delta y = b_1' + b_2'x' + b_3'y' + b_4'x'y'$$
 (4)

where  $\Delta x$  and  $\Delta y$  are the corrections to be applied to the image point. A pair of such equations is written for each of the four nearest reseau crosses which surround an uncorrected image point. The a' and b' coefficients are then found by solving four equations with four unknowns.

If all the reseau crosses are not visible, distortion corrections can still be made using a complete set of reseaus recorded earlier. The transformation equations 1 and 2 are used to fit, in the least squares sense, the current video image reseau to the reseau of the video image corresponding to the distortion correction

data file (reference video image). After the transformation of the current video image to the reference video image the transformation to the video tube faceplate is applied. The distortion correction then proceeds as above.

The video images are corrected for optical lens distortion with equations 5 and 6 once electronic corrections have been applied.

$$x = x_{cor} - \sigma x_{cor} r^2$$
 (5)

$$y = y_{cor} - \sigma y_{cor} r^2$$
 (6)

Here x and y are the coordinates corrected for distortion,  $x_{cor}$  and  $y_{cor}$  are the coordinates corrected for electronic distortion but uncorrected for lens distortion,  $\sigma$  is the third order radial distortion coefficient, and  $r^2 = (x_{cor}^2 + y_{cor}^2)$ . These equations assume that the photogrammetric principal point has coordinates of 0,0 once electronic distortion corrections have been made. The validity of this assumption, which applies to later equations as well, and the determination of  $\sigma$  and the camera constant c are discussed in reference 11.

After correcting for electronic and lens distortions the collinearity equations (12) are applied to the video images for space resection

$$x = \frac{-c(m_{11}(X-X^{c}) + m_{12}(Y-Y^{c}) + m_{13}(Z-Z^{c}))}{(m_{31}(X-X^{c}) + m_{32}(Y-Y^{c}) + m_{33}(Z-Z^{c}))}$$
(7)

$$y = \frac{-c(m_{21}(X-X^{c}) + m_{22}(Y-Y^{c}) + m_{23}(Z-Z^{c}))}{(m_{31}(X-X^{c}) + m_{32}(Y-Y^{c}) + m_{33}(Z-Z^{c}))}$$
(8)

The m terms are elements of the rotation matrix and are functions of  $\omega$ ,  $\phi$ , and  $\kappa$ —the pointing angles of the camera. X, Y, Z are the coordinates in object space corresponding to the image and  $X^C$ ,  $Y^C$ ,  $Z^C$  locate the camera perspective center. The three pointing angles and locations of the cameras in the tunnel coordinate system are found by applying nonlinear least squares to the corrected video image pairs taking c and X, Y, Z as knowns. The collinearity equations are rewritten as linear functions of X, Y, and Z and linear least squares used on each image pair for triangulation to determine the locations of wing targets after deflection.

Model deformation at the NTF is determined by subtracting the Z locations of the undeformed model from the triangulated Z locations of the deformed model. Before performing the subtraction, the deformed triangulated locations are transformed to remove any pitch or roll the model may have had when data were taken. Thus the deflected values correspond to Z displacements in the model coordinate system.

The location and pointing angles of the cameras may vary slightly during a run due to vibrations

or contraction and expansion of the tunnel as the temperature is varied over several hundred degrees Kelvin. These variations in camera exterior orientation are monitored by performing space resection on the undeformed model with wind off and at known pitch and roll angles. A plate with 33 LED's is installed on the opposite test section sidewall to that of the cameras to serve as a reference to monitor possible changes in the positions or pointing angles of the cameras.

The collinearity equations assume that the object point, perspective center, and image point all lie on a straight line. This assumption is violated for close-range photogrammetry through windows. At the NTF the effect is worsened due to the high pressure, low temperature operation. Corrections for window effects are determined iteratively when triangulating by first assuming no window distortions. The triangulated values for X, Y, Z are then used in an iterative raytrace routine to determine a first estimate of the window distortion to subtract from the image plane coordinates before repeating the triangulation a second time. The second set of values for X, Y, Z are then used to determine an improved estimate of the window distortion. This improved estimate is subtracted from the original image plane coordinates and a final triangulation performed. Space resections are performed in a similar manner except that the camera location and pointing angles are adjusted iteratively to compute the amount of window distortion which must be subtracted from the original image plane data. The iterative procedures are justified since the variation of window distortion with object position is slight (<0.005 mm/cm at 9 atm and 100 K).

## INITIAL TUNNEL EXPERIENCE

The Video Model Deformation (VMD) system was installed in conjunction with the survey rotary rake calibration runs at the NTF. This model had symmetrical 15 degree wedge leading and trailing edges and was tested at O'angle of attack so experienced no lift or consequent model deformation. The tests served to check the operation of equipment making up the video photogrammetric system. The EC (electro-conductive) coatings failed on one window during a cryogenic series. Subsequent examination indicated that the lead attachment points on the bus bars were subjected to high thermal stresses due to the disparity between the thermal expansion coefficients of the conductive epoxies and the fused silica substrate. No problems were experienced during a recent tunnel entry since current was applied to the coatings whenever the temperature dropped below 270 K, whether VMD data were acquired or not. A backup heated air purge using a circular perforated purge ring also kept the windows frost free.

The rake series also served to uncover a problem with vibration. Initial design considerations concentrated on the suitability of camera frame rates (30 Hz) to freeze most of the model dynamics. Tunnel vibrations, however, caused geometrical distortion in the video images.

Conditions worsen at higher Mach numbers and pressures and the effect is noticeable in the reseau pattern and therefore not entirely due to flow-field effects. Subsequent testing on a laboratory shaker confirmed the shimmer. The camera mounts were subsequently softened using vibration isolation pads. Improvement was noted for the limited range of conditions experienced in the latest entry (M<0.8, P<5 atm) but the problem remains. It is believed that the difficulty is inherent in the video tubes and might be avoided by using solid state cameras.

#### Pathfinder Series

The Pathfinder model is pictured in figure 5 mounted in the test section. Pathfinder I is a representative wide-body transport configuration incorporating an advanced high-aspect ratio supercritical wing to test various aspects of the new cryogenic testing technology. The first Pathfinder entry used an uninstrumented solid wing. The VMD ports are shown on the test section wall. The cameras are separated by approximately 91 cm and are located 2 m from the center of the far side wing. Aerodynamic drag considerations were waived to allow targetting of the airfoil to test the model deformation system. Machinists layout dye was sprayed on the wing and solvents used to remove target spots to expose the shiny Nitronic 40 stainless steel surface. These targets were unacceptable due to the limited lighting flexibility in the tunnel and white paint was needed to enhance the contrast of the targets. Two typical stereo hardcopy views are shown in figure 6.

Wing deflection measurements for the Pathfinder solid wing are presented in figures 7 and 8. Data taken at total temperatures of 315 K (Figure 7) and 117 K (Figure 8) are presented for comparison. Also presented in figure 7 to illustrate scatter under ideal conditions is a no-flow deflection plot. The scatter of the reduced data is comparable to the symbol size (0.5 mm). A quadratic fit to the deflected data is plotted through the data points. The deflections at the wing tip as determined by the quadratic fits for figures 7 and 8 are 7.6 mm and 8.4 mm respectively for dynamic pressures of 5.8 psi and 4.3 psi.

## CONCLUDING REMARKS

Preliminary model deformation measurements under both conventional and cryogenic conditions were obtained for a transport configuration model using the VMD system. Experimental scatter was within 0.5 mm (20 mil) over the 68 cm semi-span. A calibration scheme to resect camera positions using known roll positions under no flow conditions proved effective. Both electro-conductive defrosters and heated air purge rings maintained frost free windows and permitted high quality video imagery under cryogenic conditions. A video disk system effectively captured data within the tightly scheduled cryogenic operating sequence. Vibration induced electronic distortion associated with the camera tube construction may severely degrade video data under more severe

tunnel conditions anticipated in future NTF runs. Solid state cameras may alleviate this problem. Surface smoothness constraints were relaxed somewhat to allow for high contrast painted targets to exercise the VMD system. Effective, nonperturbing, passive targets have yet to be devised for the current approach.

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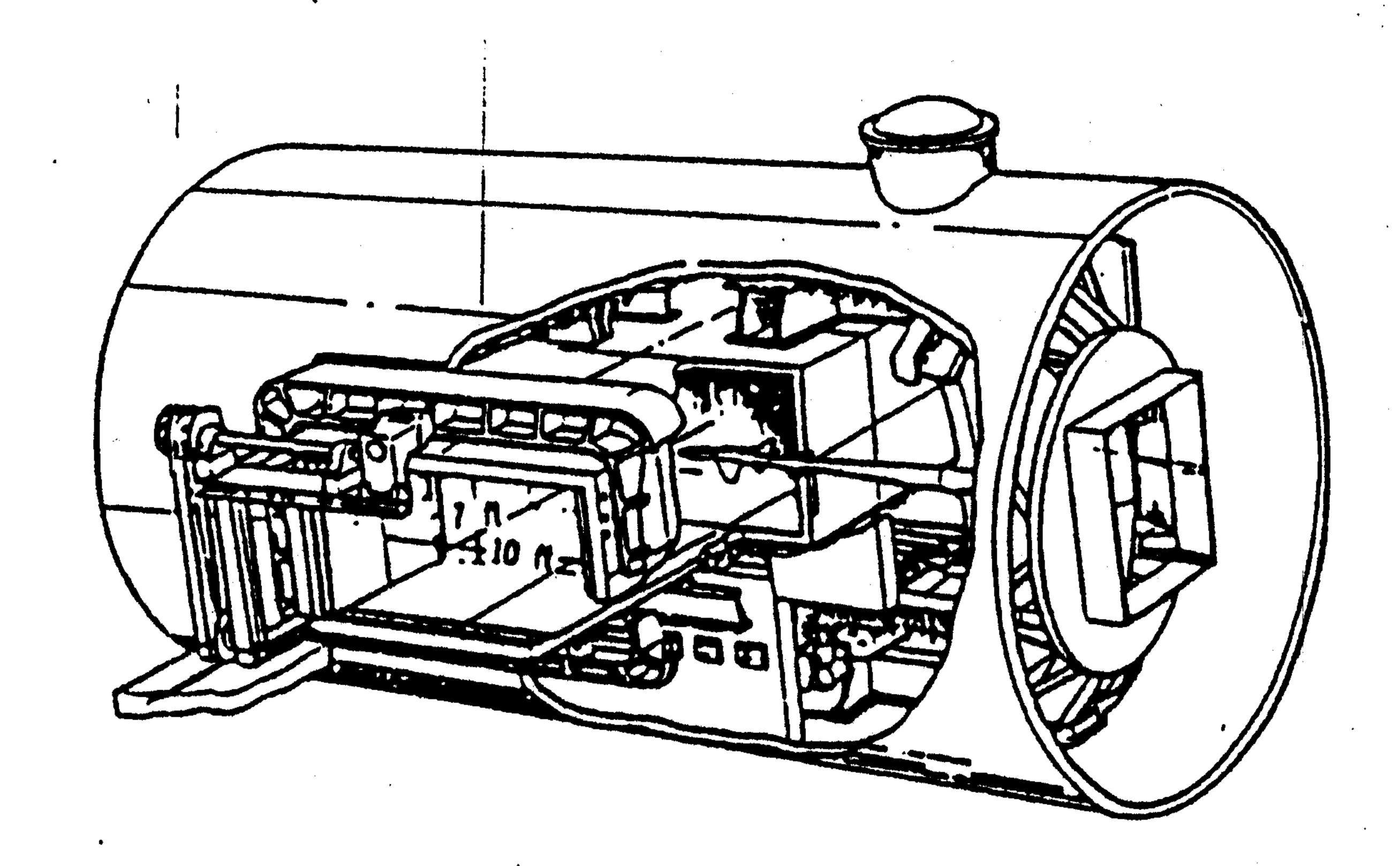


Figure 1. Sketch of test section and plenum at the NTF

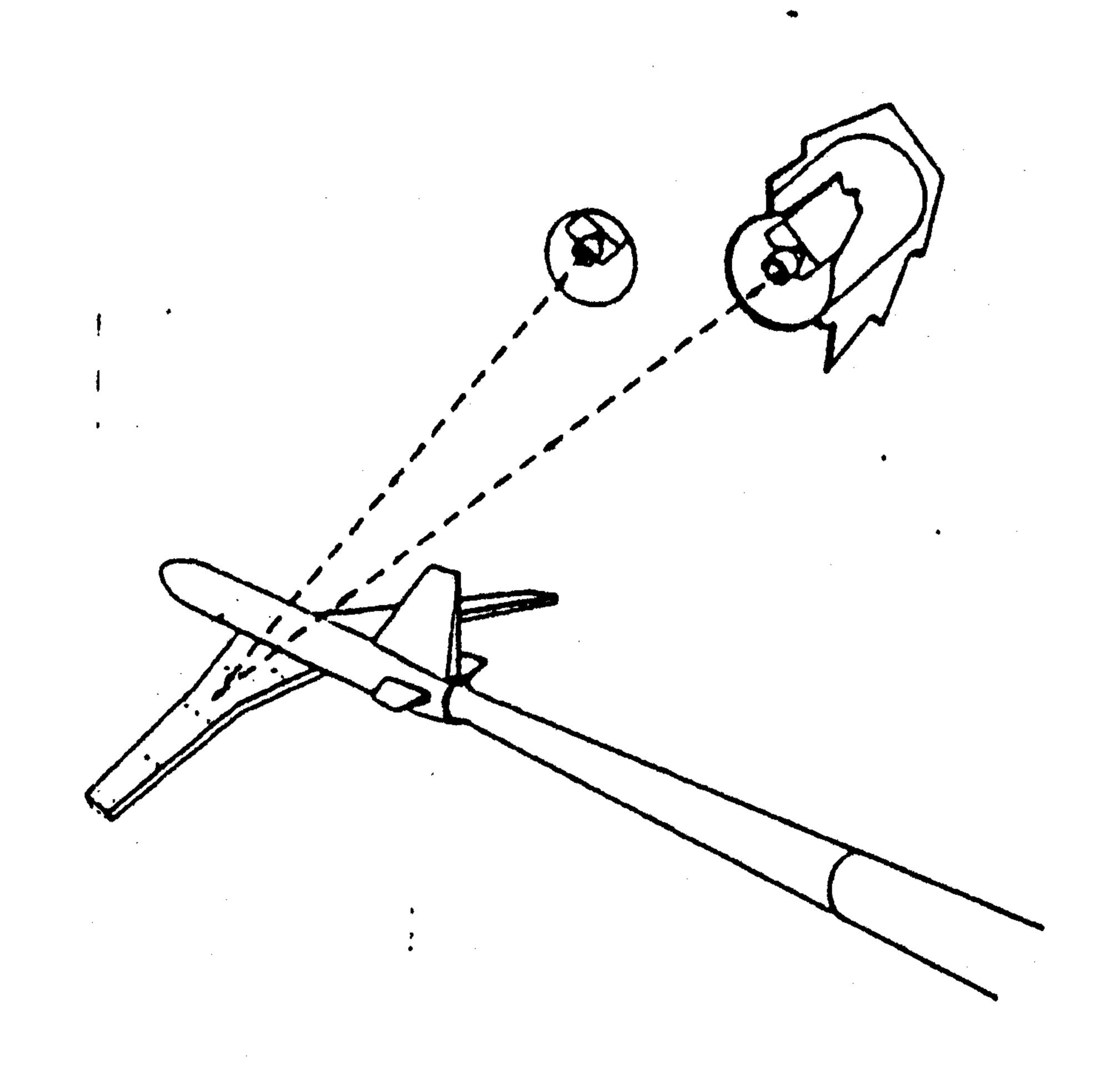


Figure 2. Experimental configuration

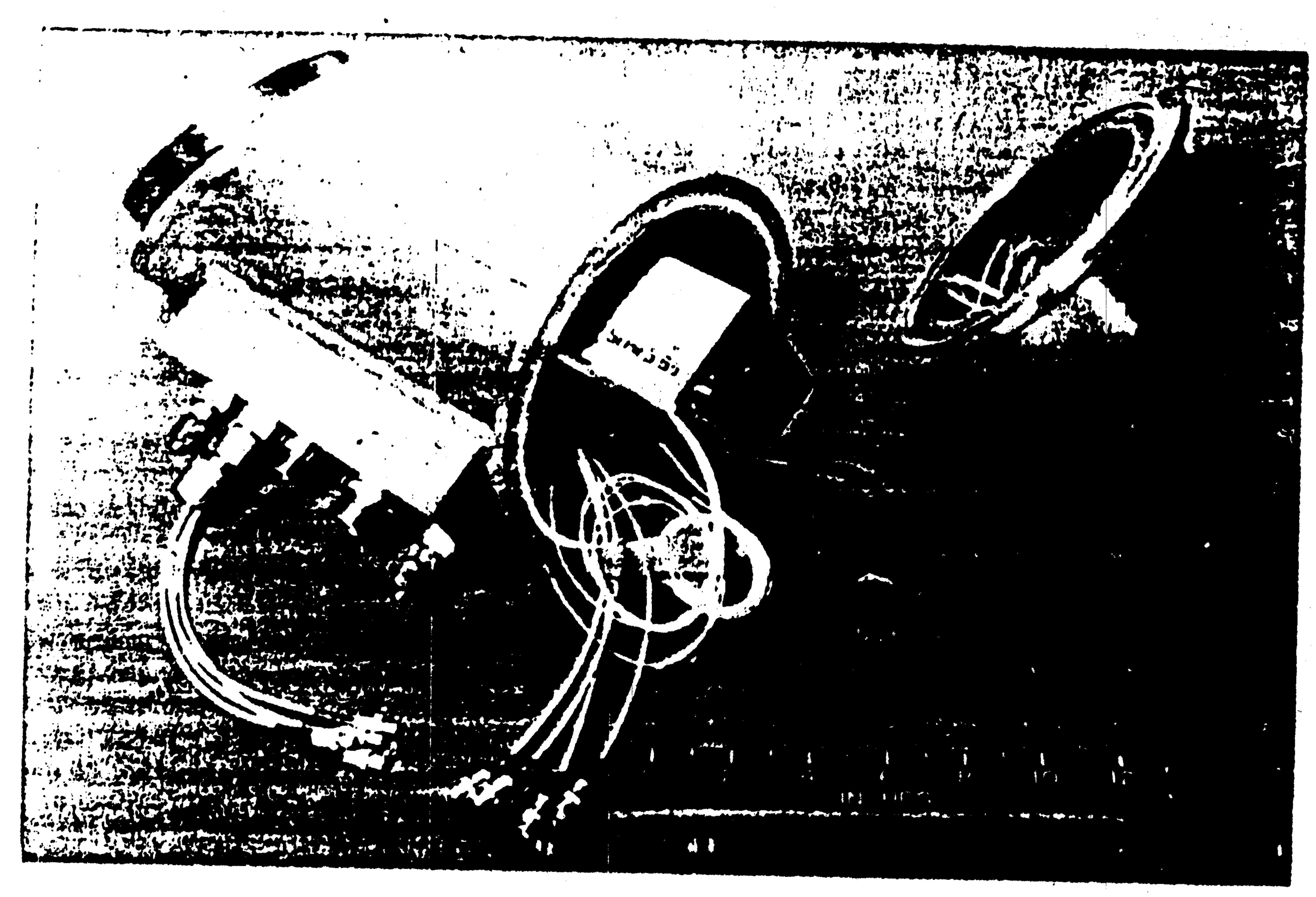


Figure 3. Protective housing at the NTF

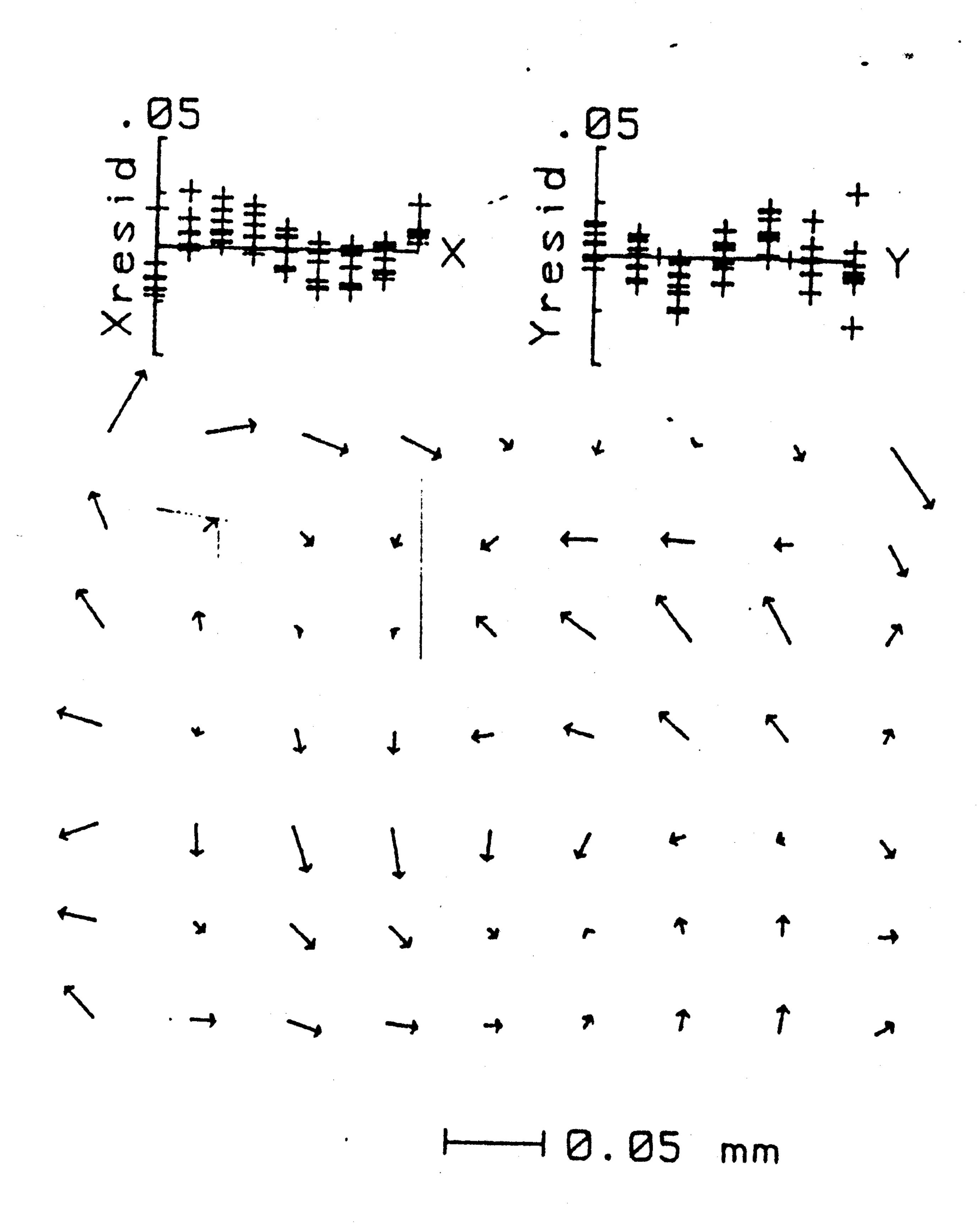


Figure 4. Electronic distortion pattern for a video camera

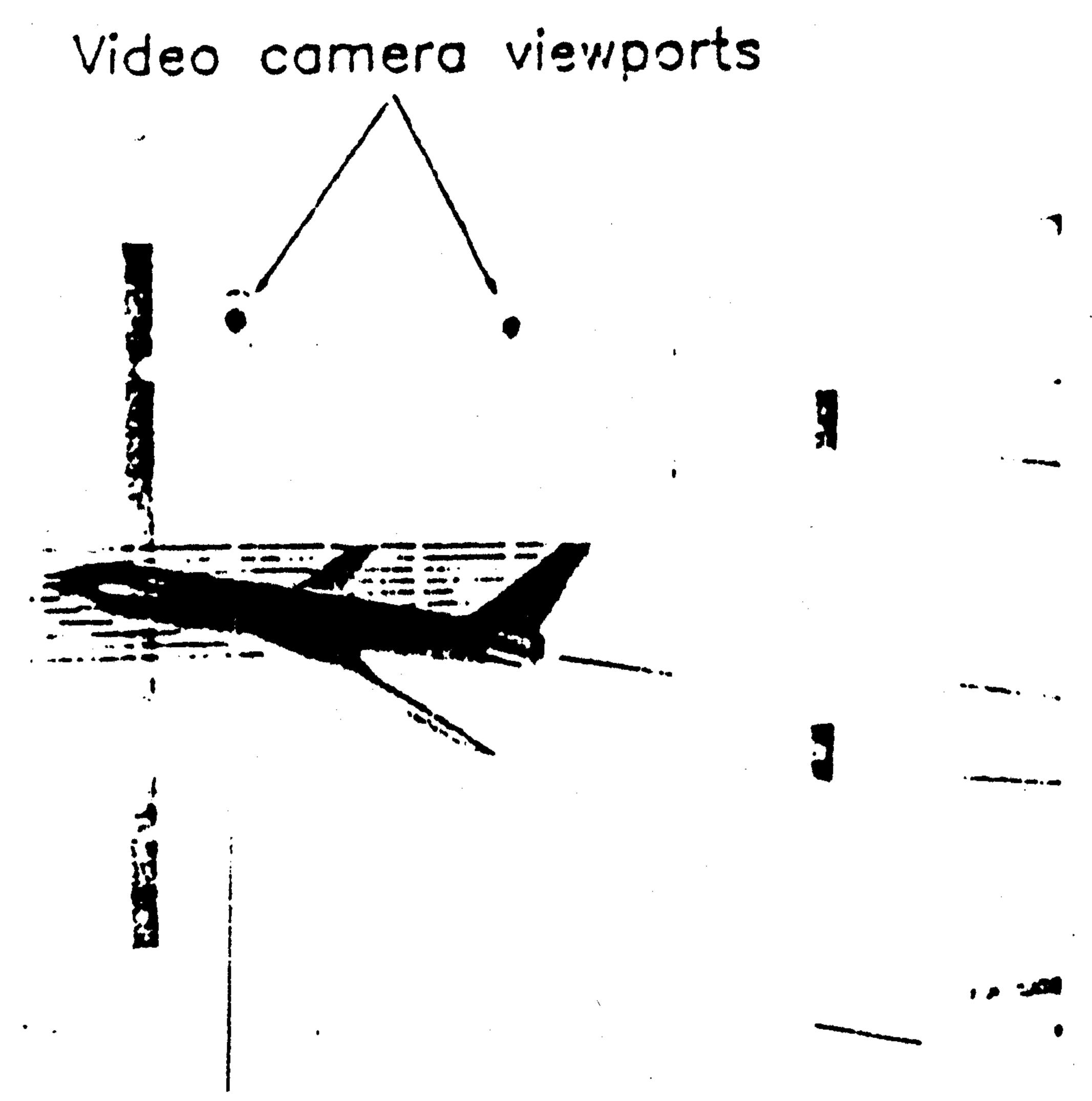


Figure 5. Pathfinder model mounted in test section

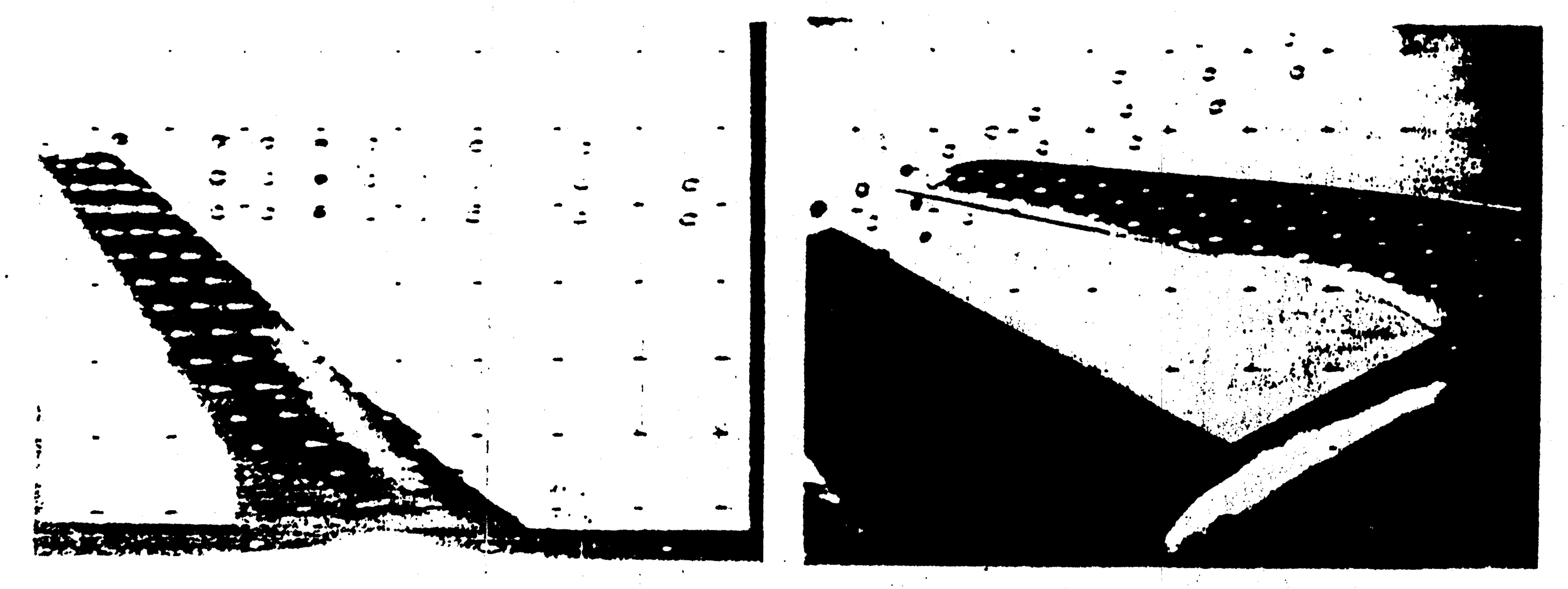


Figure 6. Hardcopy recordings of the Pathfinder model

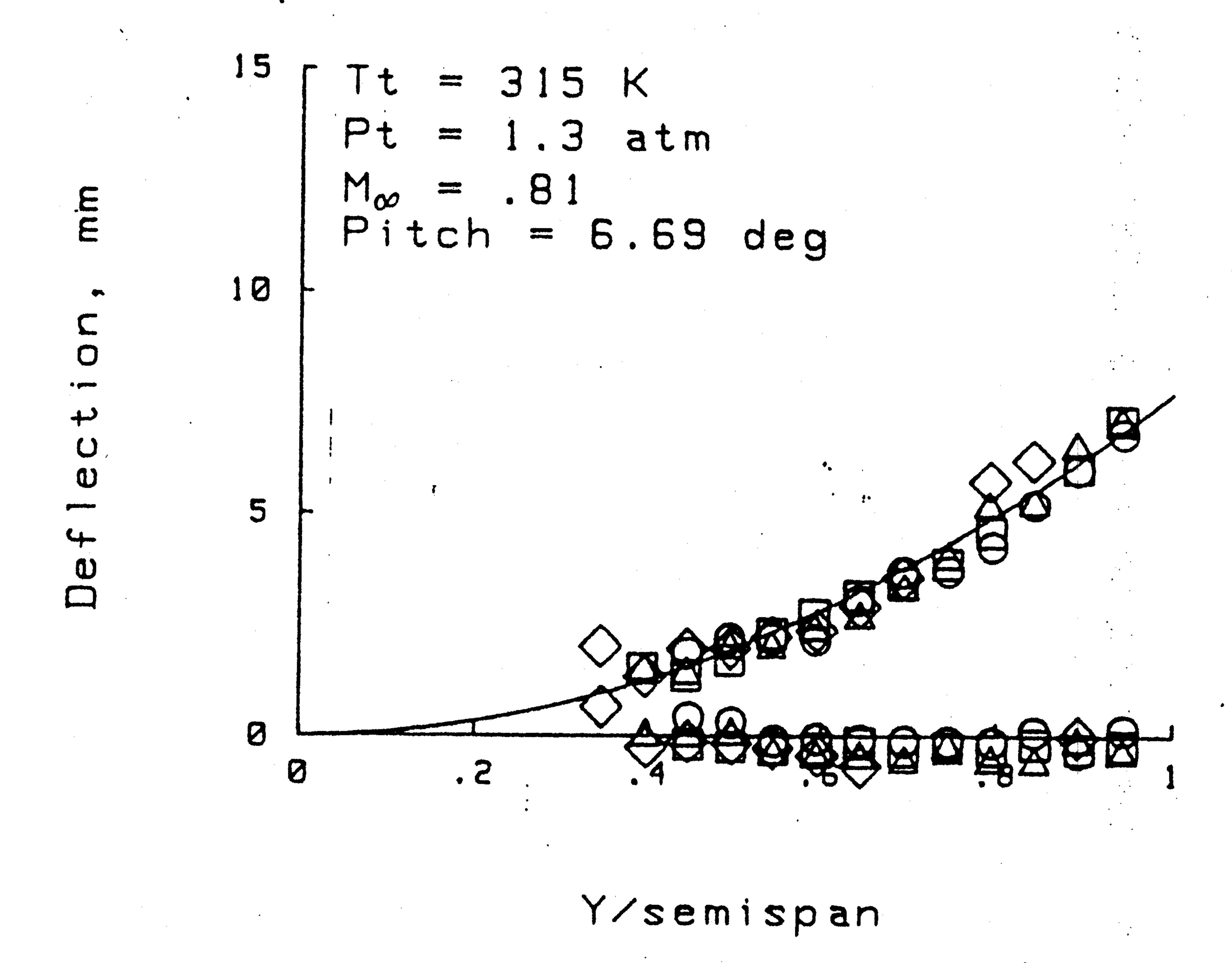


Figure 7. Measured wing deflection (ambient)

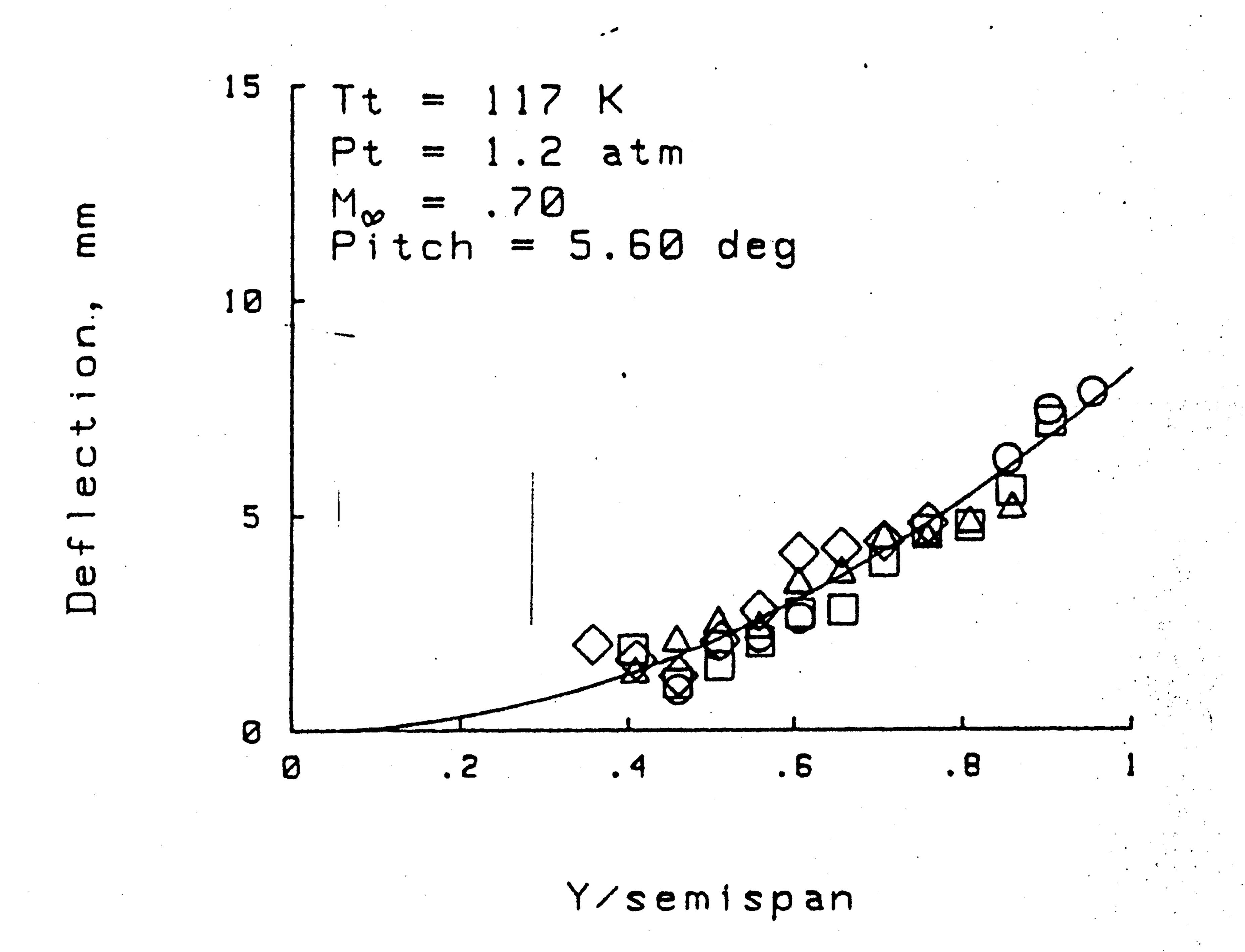


Figure 8. Measured wing deflection (cryogenic)